PERFORMANCE OF DIESEL ENGINE USING HYDROGEN AS A FUEL

NUR IZZATI BINTI KHAIRUDDIN

Thesis submitted in fulfilment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering with Automotive Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

DECEMBER 2012

ABSTRACT

Among the alternative fuels, hydrogen shows great potential in the near future. In the present study, hydrogen utilization as diesel engine fuel was investigated. Hydrogen cannot be used directly in a diesel engine due to its autoignition temperature higher than that of diesel fuel. One alternative method is to use hydrogen in enrichment or induction. To investigate the combustion characteristics of this dual fuel engine, a single cylinder diesel research engine was converted to utilize hydrogen as fuel. Hydrogen was introduced to the intake manifold using a mixer before entering the combustion chamber. The engine was run at a constant speed of 2000 rpm and variable equivalence ratio. Rate of heat release, rate of pressure rise and cylinder pressure were measured. Introducing hydrogen to the combustion chamber reduced the diesel fuel consumption.

Keywords: diesel, hydrogen, combustion, single cylinder

ABSTRAK

Antara bahan api alternatif, hydrogen menunjukkan potensi yang besar dalam masa terdekat. Dalam kajian ini, penggunaan hidrogen sebagai bahan api enjin diesel telah dikaji. Hydrogen tidak boleh digunakan secara terus dalam enjin diesel kerana suhu penyalaan lebih tinggi daripada suhu bahan api diesel. Antara salah satu kaedah alternatif adalah dengan menggunakan hydrogen dalam pengunaan atau induksi. Untuk menyiasat ciri-ciri pembakaran enjin bahan api ini, satu penyelidikan diesel silinder enjin telah dijalankan dengan menggunakan hydrogen sebagai bahan api. Hydrogen adalah diperkenalkan untuk pancarongga pengambilan menggunakan pengadun sebelum memasuki pembakaran kebuk. Enjin telah dijalankan pada kelajuan malar 2000 rpm dan nisbah kesetaraan ubah. Kadar pembebasan haba, kadar kenaikan tekanan dan tekanan silinder telah diukur. Memperkenalkan hidrogen kepada kebuk pembakaran mengurangkan penggunaan bahan api diesel.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

Δ	Time interval
Cv	Constant volume specific heat
k	Thermal conductivity
m	Total number of samples
P	Pressure
Q	Total heat transfer
R	Gas constant
T	Temperature
V	Volume
θ	Crank angle

LIST OF ABBREVIATIONS

CI	Compressed ignition
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
DE	Diesel Engine
DEE	Diethyl ether
H_2	Hydrogen
H_2O	Water
HC	Hydrocarbon
LEL	Lower explosive limit
LFL	Lower flammability limit
LP	Liquid petroleum
N_2	Nitrogen
NO_x	Nitric Oxide
SCR	Selective catalytic reduction
SO_2	Sulphur dioxide
UEL	Upper explosive limit
UFL	Upper flammability limit

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Tighter federal, state, and local emission regulations have led to a search for alternative fuels. Liquid petroleum LP gas and alcohol are currently in use in automobiles and trucks. Hydrogen is also another example of an alternative fuel. Many considerations a determine the availability, fuel consumption, safety, engine life, fueling facilities, weight and space requirements of fuel tanks, and the range of a fully fueled vehicle. Currently, the major competing alternative fuels include ethanol, methanol, propane, and natural gas.

Hydrogen (H_2) is one of the most abundant elements in the universe and is a highly promising fuel. It is an ideal fuel since it is highly flammable and produces no pollutant or poisonous emissions. The only by-products of hydrogen that is burned are water and carbon dioxide. The sun is an example of burning hydrogen. Hydrogen has an energy content of 119,221 to 141,377 kJ and an octane rating of over 130. Hydrogen had been used effectively in some engines when mixed with natural gas. Blending hydrogen and CNG at a ratio of 20 percent H_2 and 80 percent CNG results in lower emissions than similar engines that are fueled solely by CNG. Most impressive is that the blended fuel results in a 50 percent reduction in NOx. Besides producing lower emissions, hydrogen- fueled engines are 60 percent efficient.

Transportation of hydrogen from the plant to the consumer is the biggest obstacle to its use. Hydrogen is transported by pipeline or by over-the-road tankers. The use of pipelines is limited to those areas where large hydrogen refineries and chemical plants are located. Over-the-road transportation is limited to a range of about 322 km. For distances up to 1610 km, hydrogen is transported as a liquid and is the vaporized after delivery.

1.2 PROBLEM STATEMENT

There are two problem statements that have to be solved in this research. First is the prediction of the engine performance and exhaust emissions of diesel engines using hydrogen and second is effect of injection timing, engine speed, and equivalence ratio.

1.3 PROJECT OBJECTIVE

There are two main objective in that has to be achieved in this research. Main objective is to investigate the performance and emission characteristic of a single cylinder engine operating with hydrogen. The second objective is to investigate the effect of hydrogen fuel to the different performance.

1.4 SCOPE OF WORK

There are three main scopes in this research. First is doing the simulation using Fortran. Second is comparing the simulation results with other results that have done the simulation and experiment. Third is to study the behavior of diesel engine performance.

CHAPTER 2

LITERITURE RIVIEW

2.1 INTRODUCTION

In order to conduct a research, it is important to review on the aspects that related to the topic. This chapter covers the recent review of single diesel engine powered with hydrogen research activities are presented here. All the studies mainly focus on the performance and emission characteristic of the diesel engine operating with hydrogen.

2.2 DIESEL ENGINE

2.2.1 History

The diesel engine has a long history that is intertwined closely with economic and other issues of the time. The diesel engine was created by Rudolph Diesel. He developed the idea of the diesel engine and thought up the principle of its operation. He thought up the concept of the engine that compresses air to the degree where there is a resulting rise in temperature.

The concept followed the principle where when the air enters the chamber with the piston, the air ignited due to the high temperatures. This causes the piston to move down and eliminates the need for an ignition source. When Diesel designed his engine, it was at a time when there was a demand for a more fuel efficient engine as the steam engine was nowhere close to efficient.

It was on February 27th, 1892 that Diesel filed a patent in the patent office in Germany for his method and design for the combustion engine. He sourced contracts from companies that manufactured machines and began his experimentation stage. During this stage he constructed working models of his design in an attempt to construct the most efficient engine of that time.

It was in the year 1893 that he was successful in putting out the first model that was able to run with its own power and with an efficiency of approximately 26%. This was more than double the efficiency of the steam engines of that time and was a great stride for the efficient engine and a great start to the engines of today.

It was in February of 1897 that he accomplished a great achievement and produced a diesel engine that ran at 75% efficiency. This was the first one of its kind that was deemed suitable for practical use and was demonstrated at the Exhibition fair in France in the year 1898. This engine in particular was run on peanut oil and in Diesel's vision was great for the small business owners as well as farmers as it used an economical fuel source that was a biomass fuel. It was his use of a biomass fuel that continued until the 1920's and is starting again today.

When working on his calculations, Rudolf Diesel theorized that higher compression leads to higher efficiency and more power. This happens because when the piston squeezes air in the cylinder, the air becomes concentrated. Diesel fuel has a high energy content, so the likelihood of diesel reacting with the concentrated air is greater. Another way to think of it is when air molecules are packed so close together, fuel has a better chance of reacting with as many oxygen molecules as possible. Rudolf turned out to be right , a gasoline engine compresses at a ratio of 8:1 to 12:1, while a diesel engine compresses at a ratio of 14:1 to as high as 25:1.

2.2.2 Classification

The operation of a diesel engine is comparable to a gasoline engine. They also have a number of components in common, such as the crankshaft, pistons, valves, camshaft, and water and oil pumps. They both are available as two stroke or four stroke combustion cycle engines. However, diesel engines have compression ignition systems. Rather than relying on a spark for ignition, a diesel engine uses the heat produced by compressing air in the combustion chamber to ignite the fuel. The compression ratio of the diesel engines is typically three times (as high as 25:1) that of a gasoline engine. As intake air is compressed, its temperature rises to 700^0C to 900^0C. Just before the air is compressed, a fuel injector sprays a small amount of diesel fuel into the cylinder. The high temperature of the compressed air instantly ignites the fuel. The combustion causes increased heat in the cylinder and the resulting high pressure moves the piston down on its power stroke.

Figure 2.1 : Diesel engine (Source: Siew Hwa Chan,2000)

2.2.3 Construction

Diesel engines are heavier than gasoline engines of the same power. A diesel engine must be made stronger to contain the extremely high compression and combustion pressure. A diesel engine also produces less horsepower than a same-sized gasoline engine. Therefore, to provide the required power, the displacement of the engine is increased. This results in a physically larger engine. Diesels have high torque outputs at very low engine speeds but do not run well at high engine speeds. On many diesel engines, turbochargers and intercoolers are used to increase their power output.

Diesel combustion chambers are different from gasoline combustion chambers because diesel fuel burns differently. Three types of combustion chambers are used in diesel engines: open combustion chamber, precombustion chamber, and turbulence combustion chamber. The open combustion chamber is located directly inside the piston. Diesel fuel is injected directly into the center of the chamber. The shape of the chamber and the quench area produce turbulence. The precombustion chamber is a smaller, second chamber connected to the main combustion chamber. On the power stroke, fuel is injected into the small chamber. Combustion is started there and then spreads to the main chamber. This design allows for lower fuel injection pressure and simpler injection systems. The turbulence combustion chamber creates an increase in air velocity or turbulence in the combustion chamber. The fuel is injected into the turbulent air and burns more completely.

Fuel injection is used in all diesel engines. Older diesel engines had a distributor-type injection pump driven and regulated by the engine. The pump supplied fuel to injectors that sprayed the fuel into the engine's combustion chamber. Newer diesel engines are equipped with common rail systems. Common rail systems are direct injection (DI) systems. The injectors' nozzles are placed inside the combustion chamber. The piston hop has a depression where initial combustion takes place. The injector must be able to withstand the temperature and pressure inside the cylinder and must be able to deliver a fine spray of fuel into those condition. These systems have a high pressure (1,000+ bar) fuel rail connected to individual solenoid-type injectors.

The injectors are controlled by a computer that attempts to match injector operation to the operating conditions of the engine. Newer diesel fuel injectors rely on stacked piezoelectric crystals rather than solenoids. Piezo crystals quickly expand when electrical current is applied to them. The crystals allow the injectors to responds very quickly to the needs of the engine. With this new style injector, diesel engines are quieter, more fuel efficient, cleaner, and have more power.

Diesel engines are also available in two stroke-cycle models. Most diesels generally use the four stroke cycle, while some larger diesels operate with the two-stroke cycle. Two-stroke diesels must use forced induction from either a turbocharger or a supercharger. These engines are ideal for some applications because they provide high torque for their displacement.

2.2.4 Advantages

When compared to gasoline engines, diesel engines offer many advantages. They are more efficient and use less fuel than a gasoline engine of the same size. Diesel engines are very durable. This is due to stronger construction and the fact that diesel fuel is a better lubricant than gasoline. This means that the fuel is less likely to remove the desired film of oil on the cylinder walls and piston rings of the engine. Diesel engines are also better suited for moving heavy loads at low speeds.

2.2.5 Disadvantages

The primary disadvantages of using diesel engines in passenger cars and light trucks are low power output, difficult cold weather starting, noises and exhaust emission. Many diesel engines are fit with a turbocharger to increase their power. Combining turbochargers with common rail injection systems have resulted in more horsepower.

In cold weather, diesel engines can be difficult to start because the cold air cannot become hot enough to cause combustion, in spite of the high compression ratios. This problem is compounded by the fact that the cold metal of the cylinder block and head absorbs the heat generated during the compression stroke. Some diesel engines use glow plugs to help ignite fuel during cold starting. These small electrical heaters are placed inside the cylinder and are used only to warm the combustion chamber when the engine is cold. Other diesels have a resistive grid heater in the intake manifold to warm the air until the engine reaches operating temperature.

A characteristic of a diesel engine is its sound. This noise, knock or clatter, is caused by the sudden ignition of the fuel as it is injected into the combustion chamber. Through the use of electronically controlled common rail injector systems, manufacturers have been able to minimize the noise.

Emissions have always been an obstacle for diesel cars and new stricter emissions standards will go into effect shortly. Cleaner, low-sulfur, diesel fuel has been available in the United States since 2007. With new technologies and the cleaner fuels, the emissions levels from a diesel engine should be able to run as clean as most gasoline engines. Many diesel vehicles have an assortment of traps and filters to clean the exhaust before it enters the atmosphere. Some diesel engines have diesel particulate filters and catalytic converters. Particulate filters catch the black soot (unburned carbon compounds) that is typically expelled from a diesel vehicle's exhaust. Most diesel cars will have selective catalytic reduction (SCR) system to reduce NOx emissions. SCR is a process wherein a substance is injected into the exhaust stream and then absorbed onto a catalyst. This action breaks down the exhaust's NOx to form H_2O and N_2. Others will use NOx traps. Diesel engines producevery little carbon monoxide because they run with an abundance of air.

2.3 HYDROGEN

2.3.1 Definition

The lightest and most abundant element in the universe, normally consisting of one proton and one electron. It occurs in water in combination with oxygen, in most organic compounds, and in small amounts in the atmosphere as a gaseous mixture of its three isotopes (protium, deuterium, and tritium) in the colorless, odorless compound H_2. Hydrogen atoms are relatively electropositive and form hydrogen bonds with electronegative atoms. In the Sun and other stars, the conversion of hydrogen into helium by nuclear fusion produces heat and light. Hydrogen is used to make rocket fuel, synthetic ammonia, and methanol, to hydrogenate fats and oils, and to refine petroleum. The development of physical theories of electron orbitals in hydrogen was important in the development of quantum mechanics. Atomic number 1; atomic weight 1.00794; melting point -259.14°C; boiling point -252.8°C; density at 0°C 0.08987 gram per liter; valence.

2.3.2 General properties of hydrogen as a fuel

Hydrogen is a carbon free alternative fuel. Hence the formation of hydrocarbon, carbon monoxide, and carbon dioxide during the combustion can be completely avoided; however a trace amount of these compounds may be formed due to the partial burning of lubricating oil in the combustion chamber. The oxides of Nitrogen (NOx) are one of the major pollutants in hydrogen operated SI and CI engines. Hydrogen operation results in achieving higher brake thermal efficiency and also results in lower level of exhaust emissions except NOx emissions. Table 2.1 shows the fuel properties of hydrogen in comparison with diesel and gasoline .

Hydrogen possesses some features that make it attractive for use as a fuel in internal combustion engines, enabling fast, close to constant volume combustion, high combustion efficiency and low emissions. The flame speed of hydrogen is higher and hydrogen allows operation at significantly higher excess air ratios than conventional hydrocarbon fuels. This enables extended lean burn operation of the engine, potentially leading to a drastic reduction of NO_x emissions. High diffusivity and low quenching distance avoids poor vaporization problems. Emissions of carbon monoxide and unburnt hydrocarbons are practically eliminated with a hydrogen fuelled engine, as the only source of carbon will be the lubricating oil. For the same reason the engine does not emit carbon dioxide. The only non-trivial exhaust gas emissions will be nitrogen oxides, which result from the oxidation of atmospheric nitrogen under high temperatures. The ignition energy for hydrogen is low, however the temperature required for autoignition is significantly higher than that of conventional hydrocarbon fuels. Therefore, CI engines using hydrogen fuel require high compression ratios and pre-heating of the inlet air to ensure autoignition.

Table 2.1: Fuel properties of Hydrogen, Diesel and Gasoline

(Source: N. Saravanan, 2008)

SI No.	Properties	Diesel	Unleaded Gasoline	Hydrogen
1.	Auto Ignition Temperature (K)	530	533-733	858
2.	Minimum Ignition Energy (MJ)	-	0.24	0.02
3.	Flammability Limits (Volume % in air)	0.7-5	1.4-7.6	4-75
4.	Stoichiometric Air Fuel ratio on mass basis	14.5	14.6	34.3
5.	Molecular weight (g mole)	170	110	2.016
6.	Density at 160C and 1.01 bar (kg/m3)	833-881	721-785	0.0838
7.	Net heating valve (Lower) MJ/kg	42.5	43.9	119.93
8.	Flame velocity (cm/s)	30	37-43	265-325
9.	Quenching gap in NTP air (cm)	-	0.2	0.064
10.	Diffusivity in air(cm2/S)	-	0.08	0.63
11.	Octane Number Research Motor	 30 -	 92-98 80-90	 130 -
12.	Cetane number	40-55	13-17	-
13.	Boiling point (K)	436-672	311-477	20.27
14.	Viscosity at 15.5 ^{0}C, (centipoise)	2.6-4.1	3.4	-
15.	Vapor pressure at 380C (kPa)	Negligible	48-108	-

2.3.2.1 Auto ignition Temperature

The auto ignition temperature is the minimum temperature required to initiate self-sustained combustion in a combustible fuel mixture in the absence of a source of ignition. In other words, the fuel is heated until it bursts into flame. Each fuel has a unique ignition temperature. For hydrogen, the auto ignition temperature is relatively high at 585 ºC. This makes it difficult to ignite a hydrogen/air mixture on the basis of heat alone without some additional ignition source.

Table 2.2: Auto ignition temperature of comparative fuels
(Source: N Saravanan, 2008)

Fuel	**Auto ignition temperature (^{0}C)**
Hydrogen	585
Methane	540
Propane	490
Methanol	385
Gasoline	230 to 480

2.3.2.2 Ignition Energy

Ignition energy is the amount of external energy that must be applied in order to ignite a combustible fuel mixture. Energy from an external source must be higher than the auto ignition temperature and be of sufficient duration to heat the fuel vapor to its ignition temperature. Common ignition sources are flames and sparks.

Although hydrogen has a higher auto ignition temperature than methane, propane or gasoline, its ignition energy at 0.02 mJ is about an order of magnitude lower and is therefore more easily ignitable. Even an invisible spark or static electricity discharge from a human body (in dry conditions) may have enough energy to cause ignition. Nonetheless, it is important to realize that the ignition energy for all of these fuels is very low so that conditions that will ignite one fuel will generally ignite any of the others.

Hydrogen has the added property of low electro-conductivity so that the flow or agitation of hydrogen gas or liquid may generate electrostatic charges that result in sparks. For this reason, all hydrogen conveying equipment must be thoroughly grounded. Flammable mixtures of hydrogen and air can be easily ignited.

2.3.2.3 Flammability

Three things are needed for a fire or explosion to occur: a fuel, oxygen (mixed with the fuel in appropriate quantities) and a source of ignition. Hydrogen, as a flammable fuel, mixes with oxygen whenever air is allowed to enter a hydro-gen vessel, or when hydrogen leaks from any vessel into the air. Ignition sources take the form of sparks, flames, or high heat.

Flashpoint

All fuels burn only in a gaseous or vapor state. Fuels like hydrogen and methane are already gases at atmospheric conditions, whereas other fuels like gasoline or diesel that are liquids must convert to a vapor before they will burn. The characteristic that describes how easily these fuels can be converted to a vapor is the flashpoint. The flashpoint is defined as the temperature at which the fuel produces enough vapors to form an ignitable mixture with air at its surface.

If the temperature of the fuel is below its flashpoint, it can-not produce enough vapors to burn since its evaporation rate is too slow. Whenever a fuel is at or above its flashpoint, vapors are present. The flashpoint is not the temperature at which the fuel bursts into flames; that is the auto ignition temperature. The flashpoint is always lower than the boiling point. For fuels that are gases at atmospheric conditions (like hydro-gen, methane and propane), the flashpoint is far below ambient temperature and has little relevance since the fuel is already fully vaporized. For fuels that are liquids at atmospheric conditions (such as gasoline or methanol), the flash-point acts as a lower flammability temperature limit.

Flammability Range

The flammability range of a gas is defined in terms of its lower flammability limit (LFL) and its upper flammability limit (UFL). The LFL of a gas is the lowest gas concentration that will support a self-propagating flame when mixed with air and ignited. Below the LFL, there is not enough fuel present to support combustion; the fuel/air mixture is too lean.

The UFL of a gas is the highest gas concentration that will support a self-propagating flame when mixed with air and ignited. Above the UFL, there is not enough oxygen present to support combustion; the fuel/air mixture is too rich. Between the two limits is the flammable range in which the gas and air are in the right proportions to burn when ignited.

A stoichiometric mixture occurs when oxygen and hydrogen molecules are present in the exact ratio needed to complete the combustion reaction. If more hydrogen is available than oxygen, the mixture is rich so that some of the fuel will re-main unreacted although all of the oxygen will be consumed. If less hydrogen is available than oxygen, the mixture is lean so that all the fuel will be consumed but some oxygen will remain. Practical internal combustion and fuel cell systems typically operate lean since this situation promotes the complete reaction of all available fuel.

One consequence of the UFL is that stored hydrogen (whether gaseous or liquid) is not flammable while stored due to the absence of oxygen in the cylinders. The fuel only becomes flammable in the peripheral areas of a leak where the fuel mixes with the air in sufficient proportions.

Two related concepts are the lower explosive limit (LEL) and the upper explosive limit (UEL). These terms are often used interchangeably with LFL and UFL, although they are not the same. The LEL is the lowest gas concentration that will support an explosion when mixed with air, contained and ignited. Similarly, the UEL is the highest gas concentration that will support an explosion when mixed with air, contained and ignited.

An explosion is different from a fire in that for an explosion, the combustion must be contained, allowing the pressure and temperature to rise to levels sufficient to violently de-troy the containment. For this reason, it is far more dangerous to release hydrogen into an enclosed area (such as a building) than to release it directly outdoors.

Hydrogen is flammable over a very wide range of concentrations in air (4 – 75%) and it is explosive over a wide range of concentrations (15 – 59%) at standard atmospheric temperature. The flammability limits increase with temperature. As a result, even small leaks of hydrogen have the potential to burn or explode. Leaked hydrogen can concentrate in an enclosed environment, thereby increasing the risk of combustion and explosion. The flammability limits of comparative fuels.

2.3.2.4 Density and related measures

Hydrogen has lowest atomic weight of any substance and therefore has very low density both as a gas and a liquid. Density is measured as the amount of mass contained per unit volume. Density values only have meaning at a specified temperature and pressure since both of these parameters affect the compactness of the molecular arrangement, especially in a gas. The density of a gas is called its vapor density, and the density of a liquid is called its liquid density.

Table 2.3: Vapor and liquid densities of comparative substance
(Source: N Saravanan, 2008)

Substance	**Vapor density (200C, 1 atm)**	**Liquid density (at normal boiling point, 1 atm)**
Hydrogen	0.08376 kg/m3	70.8 kg/m3
Methane	0.65 kg/m3	422.8kg/m3
Gasoline	4.4 kg/m3	700 kg/m3

Specific volume is the inverse of density and expresses the amount of volume per unit mass. Thus, the specific volume of hydrogen gas is 11.9 m3/kg at 20 ºC and 1